Verbatim Input Received

Response from Brueske

Here is my concise vision of desirable characteristics for future weather radars.

Seamlessly mosaiced radar data derived from a network of automated, uniformly calibrated radars using standardized adaptable parameters. Ideally, users would not have to concern themselves with unique characteristics of various radars.

Users should be able to examine meteorological fields (such as precipitation density, hail, snow, freezing rain, turbulence, etc.) that have extracted from the radar data rather. Meteorologists should no longer have to mentally transform reflectivity values into precipitation density, radial velocity into true wind velocity, or various polarimetric fields into precipitation types.

Radar graphical output that is completely compatible with model data. Ideally the user should be able to view a seamless transition from real-time radar imagery forward in time using model output.

3-dimensional radar imagery available for any location. This would allow, for example, pilots the ability to display a real-time cross-sections, or three-dimensional depictions, of sensible weather from one location to the next. Ideally, cross-section would transition from observed radar data the departure point to model data, time matched to a pilots planned location at any time along route.

Algorithm output should be in a format readily compatible with other GIS-compatible data.

Rapid and continuous update of algorithms and depicted weather phenomena.

Response from Burgess

First of all, John, thank you for the opportunity to make this input and participate in the process of strategic planning for the NEXRAD Network and the WSR-88D radars. I believe the strategic planning task for the TAC comes at a critical time for the radar program. As you have addressed in your invitation letter, much of the program energy has been focused on the current open systems enhancement projects (ORPG and ORDA). With one milestone now mostly accomplished and the other defined and in progress, it is time to decide on future steps. Attractive new experimental radar technologies exist in the research community, but informed decisions are needed on which ones to focus because of their increased benefit at acceptable cost. Also, I believe it is time for critical decisions on the role of the radar processors in preparation of products to assist forecasters. Since research results and current practice strongly suggest that integrated systems, featuring multiple radars and multiple sensors, produce the most useful products, the NEXRAD agencies very soon need to decide if WSR-88Ds will be limited to producing intermediate radar products (data arrays) that will be inputs to integrated products generated on agency-specific processors, or if multiple WSR-88D data will be combined with other radar/sensor data in the ORPG to provide integrated products for later agency-specific display. I think this is a critical decision in the future of the NEXRAD Program.

My input will be divided into sections discussing general radar needs (unmet requirements and needs for all users), and specific needs for the service areas with which I am familiar: severe convective warnings, precipitation estimation, and short-range forecasting. In making the inputs, it will be necessary to comment on ORDA enhancements currently planned and in experimental development, but yet to be fielded in 2007, as well as enhancements/changes not yet listed in program plans. I will add a few comments about radar networking.

General Radar Input

I believe all users want WSR-88Ds to produce calibrated estimates of basic spectral moments (reflectivity, mean velocity, and spectrum width), depicting precipitation returns, wind-tracking, and clear-air returns, but eliminating all other non-precipitation echoes (ground clutter, AP, birds, insects, particulate matter, interference from other radiation emitters, etc.). Production of such “clean data” is limited by many issues such as the properties of the real-time moment estimators, the Doppler Dilemma (range folding/velocity aliasing), and others. I know that certain enhancements are already being developed for the ORDA (phase coding, PRF agility, Radar-Echo Classifier, and others), and they will help produce a generation of better data. However, I believe that the best answer to production of “clean data” lies in accomplishing true spectral processing on the time-series data received at the ORDA. Only in the spectral domain can the “best” separation of precipitation - non-precipitation returns be produced. Real-time spectral processing previously required more computer power than was available on a cost-effective basis, but I believe the situation has changed, or will continue to change as new computer processing power is achieved, such that real-time, full spectral processing is now possible. If those smarter than I verify these statements, steps should be taken soon to begin preparing for a post-2007 generation of spectral-processed data.

The other important new capability being developed, but not yet accepted for the operational baseline, is polarization diversity. Initial testing on a WSR-88D has begun (the Joint Polarization Project) and initial results suggest that important new enhancements will be available to help separate precipitation from non-precipitation particles, determine precipitation particle types, and better estimate precipitation amounts. If these early results are confirmed by full testing, then an important enhancement for the post-2007 era will be the addition of dual-polarization data. Not yet solved are the problems associated with merging dual-polarization capability with other ORDA-era moment estimation and non-precipitation (clutter) return removal. Considerable new work will be needed in the area of signal processing. Also, accurate calibration of dual-polarization variables must be planned and accomplished in the field.

I also have comments pertinent to each of the Doppler moments:

<u>Reflectivity</u>: Currently, in my opinion, the biggest limitations associated with reflectivity data are calibration and resolution. Current absolute calibration of the WSR-88Ds (the value of returns for a specific volume of scatterers, sometime measured by comparing one radar with another) is at an unacceptable level. Such a statement is easily verified by observation of multiple-radar mosaics and the "boundary jumps" that are observed. As part of NSSL experimental algorithm development, I have access to software which produces equal-range/same-height comparisons of reflectivity from pairs of radars for three mosaic domains in the U.S. These results dramatically illustrate the depth of our current problems. It is my belief that the current NEXRAD calibration procedures are labor intensive, are not complete, and that the NEXRAD agencies have been unwilling/unable to devote the resources necessary for acceptable calibration. Therefore, completely new approaches to relative (partial) and absolute calibration need to be developed. I am aware that the ORDA-associated digital receiver will help with calibration, but probably does not address all components of "good" absolute calibration. I think more calibration development work is still needed. The other problem is resolution. Forecasters need images and certain algorithms (see below) need digital data with 0.25 km resolution. Currently, needed reflectivity accuracy is achieved (without slowing the antenna and getting more samples) by averaging four 0.25 km gates to produce 1 km data. New processing techniques of oversampling/whitening need to be developed to produce accurate 0.25 km reflectivity estimates. NSSL has just produced an ORDA-Enhancement White Paper that discusses some of the potential oversampling/whitening techniques.

<u>Velocity</u>: Currently, in my opinion, the biggest limitation associated with use of velocity data is range folding and velocity aliasing. As already mentioned, much better mitigation steps are being developed (phase coding and PRF agility). These need to be continued and implemented. Also, as already mentioned, further, longer-term development of full spectral processing needs to undertaken to completely solve the problems. The final solution needs to allow for accurate estimation of velocity in the non-precipitating boundary layer, weak returns associated with frozen precipitation (snow/ice/freezing rain-drizzle) and in the weak echo areas of thunderstorms, as well as in stronger return areas of rain and hail.

<u>Spectrum Width</u>: Currently, in my opinion, this is the forgotten measurement of the WSR-88Ds. This is because of errors in the hard-wired moment estimator that the NEXRAD agencies chose

not to fix until ORDA development, the lack of initial bandwidth to transmit all radar products to users, and the lack of emphasized training on the uses of the data. ORDA will bring accurate spectrum-width estimates. Bandwidth issues to bring the data to users will need to be addressed (see Networking comments below). Continued basic research (like that in OAR in past times, and some currently being funded in non-NEXRAD FAA research) is needed to understand how to use the new, accurate estimates. The research results need to be applied to WSR-88D products, and those applications need to be made part of comprehensive training packages. I think the training job might be particularly challenging...since we have "taught" forecasters not use spectrum-width data...it will be even more difficult to teach them to use the data.

Severe Convective Warning Input

The timing of this input is fortunate because it comes at the same time that I am serving as part of a NOAA Integrated Product Team (IPT) to develop severe storm service goals (out to 2012) and requirements to meet the goals. Of course, radar is being seen as a critical input to future service improvements. The biggest radar issues for severe convective storms are timeliness of the data, resolution of the data, and construction of multi-radar, multi-sensor application with which to support the forecaster. Some timeliness issues will be handled by already-scheduled enhancements (faster VCPs and Rapid Update for algorithms). However, other attractive future enhancements (e.g. dual polarization) will put additional burdens on the achievement to timely severe storm data. Initial NOAA IPT requirements...still in early draft form...specify vertical volume-scan times of 3 minutes and low-level scans to detect vortex/tornado changes every 1 minute. Velocity and reflectivity resolution are big issues for vortex/tornado detection. The NSSL ORDA White Paper discusses ½ deg azimuthal sampling and its advantages. The ½ deg sampling will be critical to improvements in radar inputs to tornado warnings. Basic research is reaffirming the relationship between hook echo details (size, amount of precipitation, etc) and tornado formation. Therefore, 0.25 km reflectivity data/images will be important to improvements in tornado warning lead-time. Processing steps to produce accurate high-resolution data need to be emphasized. Ultimately, phased-array-type technology will likely provide the most critical improvements for severe-storm sensing, but application of phased-array technology is probably beyond the time period associated with this input. Since timely and high-resolution sampling of the storm boundary layer and complete storm depth is important to convective warnings, the use of multiple radars becomes mandatory. Only nearby radars can sample the boundary layer (because of radar horizon limitations) while more distant radars are needed to get a good view of the entire storm (given maximum elevation angles of ~20 deg). It is not yet clear, at least to me, whether or not data from other radars (FAA radars and private-sector radars) will be a part of WSR-88D ORPG processing (see comments at the beginning). In addition, some of the needed information for warning improvement comes from other sensors (satellite, numerical model assimilations/forecasts, total-lightning mapping, and others). The NEXRAD agencies need to decide how much, if any, of the multi-radar, multi-sensor processing will be done in ORPGs and how much will be done in agency-specific processors. That answer will drive the future course of sever-storm radar algorithm development and relation of NEXRAD. A final comment is that the time period of our planning is the same as the time period where numerical modeling is anticipated, at least by some, to reach a maturity level where real-time storm-scale modeling might contribute to convective warnings, thereby increasing lead times to levels beyond those possible with detection of developing features like mesocyclones and TVSs. What, if any, is the role of the NEXRAD Program and the radars (beyond providing accurate calibrated data) in the coming multi-sensor assimilation and modeling era?

Precipitation Estimation

Issues associated with quantitative precipitation estimation (QPE) can be divided into two time periods: before and after the likely addition of dual-polarization techniques. Before dual polarization, the most pressing need is absolute calibration (see above). In order to transform QPE into stream flow in distributed catchments of different size (things that produce flash flooding), there is need to use multiple radars. To get the correct QPE amounts, it will be necessary to employ multiple sensors (satellite, rain gages, numerical model output, and other inputs). Again, as with severe storm work, it is unclear how much of the processing should be/ will be done with ORPG and how much will be done elsewhere. I suspect other NWS processing systems will be used because of the lack of tri-agency requirement for QPE. After potential dual-polarization addition, some of the calibration issues may lessen because of the advantages of specific differential phase (Kdp). Also, new QPE algorithms will be needed that take advantage of dual-polarization improvements. However, in general, I suspect the above comments about multi-radar and multi-sensor will still apply. Calibration of dual-polarization variables used for QPE will be an important future issue.

Short-Range Forecasting

One of the important advantages of the WSR-88Ds is their ability to detect boundaries in clear air and associated with non-precipitating clouds. Most often, this occurs with the clear-air mode where sensitivity is improved by ~ 20 dB (Long Pulse) and ~10dB (Short Pulse) over precipitation mode. I have three points about boundary detection. First, as many close to the NEXRAD Program know, the Long-Pulse mode is not much used, probably because of the small velocity measurement (Nyquist) interval and large amounts of aliased velocity. No separate velocity dealiasing has ever been developed for Long-Pulse mode. If Long Pulse is to continue in the ORDA era, improvements need to be made to make the mode more useful. Second, the clear-air, Short-Pulse mode is much used by forecasters to identify boundaries. However, the ~10 dB sensitivity addition is lost when the switch to precip mode occurs. This results in significant loss of boundary detection...a finding that was confirmed during the recent IHOP Experiment. Some method to improve dynamic range in precip mode is needed so that the boundary detection capability is preserved. Third, algorithms for automated boundary detection will almost certainly by multi-radar and multi-sensor (satellite, surface data, and other inputs). Therefore, the same comments apply about whether or not to do processing in the ORPG. Of course, WSR-88D data will be important components of mesoscale assimilation and model systems. Precipitation particle typing produced by dual-polarization algorithms may be crucial to model microphysics necessary to forecast storm types and storm formation and evolution. Again, as with storm-scale modeling, what is the place of the radars and the program in future numerical forecast systems?

Radar Networking

An important issue in network design is the decision to use/transfer products made from base data (aka Level-II or wide-Band data) or to transfer the base data itself. This important decision is now before the NEXRAD agencies as they decide their wide-band data handling/distribution policy. I hope the agencies will establish robust strategies and are capable of evolving with continuing technology/bandwidth increases. I would remind the agencies of the problems caused by use of antiquated communications like the 9.6 and 14.4 kB speed communications lines that have been in place for the first decade of network life. In part, the theme of this input has been multi-radar and multi-sensor strategies. No matter how or where the multi-radar/multi-sensor work is carried forward, robust, wide-band communication links will be necessary to move radar data/arrays to places where they need to go.

Response from Desrochers

The present day NEXRAD is a true marvel of science, engineering, and technology. The once visionary concept of nationwide Doppler coverage has proved to be an indispensable tool of the modern weather service. As revered as it is today, NEXRAD might not be so well admired if it had remained static in design. The key to NEXRAD's success is its continual refinement. In NEXRAD there has been a willingness to incorporate technological and scientific advances. Through careful study and planning, numerous system deficiencies have been systematically addressed and corrected. Several important refinements are underway today. The arrival of the long anticipated upgrade to signal processing will bring tremendous improvements in Doppler accuracy and coverage. Hope is held for the eventual implementation of a dual polarization upgrade and improved precipitation estimates through specific differential phase shift (KDP).

Improvements to NEXRAD over the last two decades have properly focused on upgrades to the WSR-88D. The NEXRAD network has largely remained static over the life of the project. The next phase of NEXRAD improvements should focus on improvements to the network resolution. The coarse spacing of the NEXRAD radars results in several critical deficiencies:

A) Low level coverage (< 1 km altitude) is provided for only 35% of the US land area. This problem is further exacerbated by beam occultation. Overshooting of low-level precipitation is a common problem. Low-level wind shear events are not detected.

B) High resolution coverage (< 1 km half-power beam width) is restricted to about 15% of the US land area. Most tornado cores are not detected by WSR-88D.

C) Coverage for any particular area of the network is subject to single point failures. Holes in the national coverage occur whenever one radar is off-line for maintenance.

D) The long path between WSR-88D radars precludes multiple Doppler wind retrievals. Detailed wind information for Nowcasting and numerical model initialization is not available.

In the coming decades I believe the NEXRAD network must be upgraded to provide a minimum of 1 km beam width resolution and1 km minimum height coverage over the US. Unfortunately, the inherently large cost of the WSR-88D prohibits drastic increases in their numbers within the NEXRAD network. One means of addressing the network resolution deficiencies is to utilize other existing radar networks, as MIT/LL is proceeding to do with the NEXRAD, WSR9 and TDWR systems. I believe this is a good short-term goal to addressing data gaps, but will not achieve the stated resolution needs. Since precipitation accuracy is a primary requirement of NEXRAD, all radars within the NEXRAD network should eventually have dual-pol capability.

A novel solution to the network resolution deficiencies is a high-density network of inexpensive X-band radars. This idea, discussed in the Committee report on Weather Radar Technology Beyond NEXRAD, is a logical solution that is worth exploring. X-band offers considerable cost/performance benefits compared to other wavelengths. At the component level, X-band is quite reasonably priced. There has been extensive commercial development of X-band for marine use, for example, resulting in inexpensive designs. Inexpensive, dual-pol X-band systems exist today. On the downside, X-band suffers from attenuation in heavy precipitation. This problem would be largely overcome by the use of a high-density network.

Somewhere between 500 and 1,000 X-band systems will be necessary to achieve the stated coverage goals for the US. Given the long lead-time needed to develop and implement such a system, it would be pragmatic at this time to explore this idea through the use of mobile X-band systems. Test bed networks should be assembled in various climatic zones of the US using mobile X-band radars. It is envisioned that the final network would be assembled at fixed sites. The small footprint of an X-band system makes it suitable for mounting on the top of buildings and on cellular towers. Creative solutions to placement should be pursued to minimize installation costs.

It is imperative that future radars have a modular design and self-monitoring capability. The radars must be constructed for reliable, trouble-free operation. The systems should be energy efficient and operate in all weather conditions. The transmitter, antenna, pedestal and component level elements should be should be selected according to the latest, cost efficient technology. The prospect of a high-resolution radar network will offer many opportunities for commercial development. The Government need not bear the entire development cost. Commercial partnerships should be pursued. Television stations and universities may be persuaded to share in the cost of these systems.

I believe the WSR-88D can play an important role in the NEXRAD agency missions over the next two decades. Our long-term vision of NEXRAD should include a mixed frequency network. In many regions of the US a high-resolution network of X-band systems would provide sufficient coverage without the need for the WSR-88D. The displaced WSR-88D's should not be discarded, but rather relocated. The advantage of S-band for long-range surveillance is particularly relevant to our coastline. 100 WSR-88D radars would provide 50 km spacing along the coastline of the contiguous US.

There are many technical challenges to constructing an integrated radar network. I believe the primary challenges we will face are political in nature. As the ongoing battle with cellular towers demonstrates, there is a public sensitivity to "radiation" sources. We will likely also face increased pressure from industry for greater access to the radio spectrum. The NEXRAD TAC and PMC must be proactive in securing our continued utilization of the radar bands. I applaud the desire to lay out a long-term vision and strategic plan. It is timely. I am hopeful that our efforts will be successful in providing a NEXRAD that is full of innovation for the future.

Response from Dunn

Thank you for soliciting my comments on the emphases for the NEXRAD Program for the 2007-2020 time frame. I read with considerable interest the NRC publication " Weather Radar Technology Beyond NEXRAD" that you sent to me. Although the target time frame of that publication was approximately 2020 and beyond, there were a number of near term recommendations made in the report, and I endorse all of the near term recommendations made by this group. My own area of expertise is in operational forecasting in areas of complex terrain and the comments that follow will be generally confined to this specialty in that I assume you have also sought input from others to cover the broad spectrum of issues associated with use of the NEXRAD in other geographic regions. I have broken down my comments into three main areas, Coverage, Utilization of velocity observations, and Scanning strategies.

1. Coverage:

Coverage is the single most important issue that requires attention in the 2007-2020 time frame in areas of complex terrain. The recent paper by Maddox et al. (2002) shows in graphic detail how very poor the 88D coverage is within 1km AGL over much of the United States and particularly in the West. Without coverage near the ground, it is difficult and often impossible to issue accurate forecasts and warnings for many phenomena. Accurate estimates of precipitation, particularly in low-topped convection and stratiform situations are problematic due to coverage problems. Warm rain processes are particularly important in many rain on snow flooding events, and these are poorly sampled due to beam overshooting. Similarly, many 88Ds sample primarily at and above the melting level in many winter storms, again resulting in nearly useless precipitation estimates. Microburst winds are not observed because they are not even seen due the poor coverage in most of the West, and at moderate range in the rest of the country. The same is true of low-level boundaries. Initiation of convection due to boundary interaction is virtually impossible to predict in the West due to nearly non-existent coverage of the boundary layer. The list of phenomena that are either poorly sampled, or completely missed due to inadequate coverage could go on and on.

In many parts of the country, the problem of limited coverage of the lower portion of the atmosphere may be difficult to solve without the installation of additional radars. However, in locations where the 88D is located at a higher elevation than the surrounding terrain, coverage could be improved by new scanning strategies that allow for data collection with the center of the beam lower than 0.5 degrees (Brown et al. 2002). Vincent Wood, Rodger Brown, and Steve Vasiloff have a paper in review with the journal of Weather and Forecasting, entitled "Improved detection using negative elevation angles for mountaintop WSR-88Ds: Simulations of the three radars covering Utah". This paper suggests that coverage could be significantly improved at high elevation radars by adopting a scanning strategy optimized for each site. I strongly encourage the NEXRAD TAC to investigate the feasibility of implementing this approach.

The inclusion of data from non-WSR-88D radars, particularly in regions of poor coverage by the 88Ds should be investigated. This would include the TDWR and non-federal radars. This recommendation was also made in the aforementioned NRC report. Observations from a few TDWRs are being used operationally already, but they are not in any way merged with data from the WSR-88D. The combing of observations from these two radars has the potential improve the utility of both systems for all users.

2. Utilization of velocity observations:

Observations of velocity derived from Doppler radar provide tremendous value in the real-time evaluation of potentially severe convection. However, outside of their use in the context of severe convection, velocity data are vastly underutilized. This is particularly unfortunate since a more comprehensive understanding of the wind field would be of considerable value in understanding and forecasting the mesoscale processes and phenomena that dominate the actual weather experienced by people. Although VAD winds are heavily used and efforts continue to assimilate 88D velocity observations into NWP, plan view displays of velocity imagery are a sub-optimal use of this resource.

The best use, outside of severe convection, of velocity observations from the 88D will be within sophisticated analysis schemes at horizontal resolutions of 2km or less, that merge these data with other wind observations in a real-time cycle of at most 15 minutes, and preferably less. These other observations include mesonet winds, ACARS observations, vertical profilers, rawinsondes, other radars, and indirect measurements of wind from satellites and other remote sensors. I urge the NEXRAD TAC to build upon the recent open systems upgrades to NEXRAD and those planned for the next few years to make real-time radar observations available in a timely and convenient manner to serve as a cornerstone of advances in local analysis techniques. A synergistic combination of radar experts and analysis experts should be nurtured to bring about real advances in this area.

In addition to and in conjunction with the incorporation of 88D observations into sophisticated local analysis, the NEXRAD program should be looking at ways to derive dual-Doppler velocity observations wherever possible. This may be possible in areas where there is overlap in 88D coverage, and more likely in locations where non-NEXRAD radars and 88Ds are both scanning the same volume. This is certainly possible where the TDWR is operating. There are a number of technical issues associated with obtaining dual Doppler observations from disparate radar systems, but it can be done. It may be that this effort is only worthwhile in non-clear-air situations where multiple radars are likely to be able to sample the velocity field, but I believe this would be very beneficial, particularly in winter storms. The output of this effort should include observations to be included in the aforementioned local analysis effort, as well as CAPPI-like displays for immediate use.

Finally, in an effort to improve velocity data utilization, I believe it is worth looking into operational deployment of bistatic Doppler radar receivers (Wurman et al.1993). While there are a number of technical issues to be resolved, it may be possible to derive great benefit from this approach in the 2007-2020 time frame.

3. Scanning strategies:

Even with the coverage problems associated with the current NEXRAD network, we can do better at observing various phenomena by employing alternative scanning strategies. Microbursts and non-supercell tornadoes, to name just two phenomena, develop on time scales that we will never adequately sample with our current scan strategies. New scanning strategies are already under development and deployment will occur in the near term, but efforts should continue to identify the optimal method of observing key phenomena with the 88D. This effort should include the customization of scan strategies for individual 88D installations, taking into account blockage, clutter, and elevation above the surrounding terrain. It may be desirable to develop scan strategies that are particularly tuned to observe certain expected or already occurring phenomena. Although it may be more difficult to manage a larger number of scan strategies throughout the network, I urge the NEXRAD TAC to consider very seriously the abandonment of the "one size fits all" approach that has characterized the system thus far.

References:

Brown, R. A., Vincent T. W., and T. W. Barker, 2002: Improved Detection Using Negative Elevation Angles for Mountaintop WSR-88Ds: Simulation of KMSX near Missoula, Montana. *Wea. Forecasting*, Vol. 17, No. 2, pp. 223–237.

Maddox, R.A., J. Zhang, J.J. Gourley, and K.W. Howard, 2002: Weather Radar Coverage over the Contiguous United States, *Wea. Forecasting.* Vol.17, pp. 927-934.

Wood, V. T., R. A. Brown, and S. V. Vasiloff: Improved detection using negative elevation angles for mountaintop WSR-88Ds: Simulations of the three radars covering Utah, in review, *Wea. Forecasting.*

Wurman, J., S. Heckman, and D. Boccippio, 1993: A Bistatic Multiple-Doppler Radar Network. *Journal of Applied Meteorology*, Vol. 32, No. 12, pp. 1802–1814.

Response from Evans

This letter is a response to your request for suggestions of the emphases for the NEXRAD program long-term vision and strategic plan for the 2007-2020 time frame.

I recommend that much greater emphasis should be on increasing NEXRAD value for the non-meteorologist end users (including numerical model usage) in the context of an integrated observation system. These are key objectives in the "beyond NEXRAD" report that could be significantly achieved in the 2007-2020 time frame.

There are two key elements of this thrust:

> Widespread "direct" dissemination of NEXRAD derived products to non-meteorologist end users, and
>
> Automatically generation of the products through use of an integrated observation system, mosaics, data assimilation, nowcast algorithms and numerical models

This recommended emphasis is quite at variance with what historically had been the NEXRAD focus: providing weather data to meteorologists who would issue the forecasts for non-meteorologist users.

However, there have been very rapid changes in the NEXRAD usage in the past few years:

a. Since 1994, the FAA has been operationally providing fully automated products that use NEXRAD as part of an integrated observation system [the Integrated Terminal Weather System (ITWS)]. The product generation technology utilized for ITWS includes mosaicing, nowcasting, and data assimilation. Production ITWS systems are in operation now at 4 major terminal areas with installation planned for another 30 terminals in the near future.
b. Private vendors and the government are distributing NEXRAD products directly to non-meteorologist users and, using NEXRAD products in conjunction with other weather data to automatically create additional products for direct use by non-meteorologists.

Both of these direct uses of NEXRAD data by non-meteorologist users and fully automated product generation systems will grow significantly in the very near term.

Base data quality improvements

At MIT's Lincoln Laboratory, we have been developing fully automated weather products using Doppler weather sensing radars (e.g., TDWR, ASR9, NEXRAD) for use by non-meteorologists (e.g., controllers, traffic flow managers, pilots, airline dispatch)

since the early 1980's. Our experience has been that achieving the requisite high integrity for the end user weather products in this application requires very careful attention to the data quality at the radar sensor and, at the data assimilation/mosaicing/nowcasting stages.
To date, NEXRAD has been a bit of a disappointment in achieving high integrity in base data quality and, end user products. Since both the NWS and USAF focused on experienced meteorologist interpretation of the NEXRAD data and products, many of the data quality problems discussed in the "beyond NEXRAD" report (e.g., normal and anomalous propagation ground clutter, range/velocity folding, returns from birds and insects, radar interference, sun radiation and technician induced anomalies) have not been adequately addressed to date. In some cases, there was significant opposition at the OSF to mitigating some data quality problems out of concern that weather detection might be adversely impacted.

The Open RDA and RPG plus the dramatic drops in communications costs and computer costs/memories offer an opportunity to make a dramatic improvement in NEXRAD data quality in the near term. For example, it will be possible to have multiple base data streams available so that applications are able to use base data with an application specific set of data quality improvement steps applied to it. It also is much more feasible to move full resolution data to an integrated observation system processing location to further improve the data quality as well as creating new, integrated products.

I envision two key thrusts in data quality improvement:

1. Current and future efforts to improve the data quality at the NEXRAD sensor level need to be much better integrated with concurrent research to create fully automated products (by data assimilation/mosaicing/nowcasting) for use by non meteorologists and, have beta test sites in a variety of climatic/meteorological regimes. Specifically, once base data quality improvement techniques in areas such as:

    Normal and anomalous propagation ground clutter
    Out of trip weather
    Velocity folding
    Radio frequency interference (including "sun strobes")
    Improper radar maintenance
    Non-atmospheric reflectors such as birds

    have gotten to a point of showing promise to warrant inclusion in the NEXRAD, there needs to be testing with candidate automatic product generation algorithms at a variety of beta test locations before the improvement techniques are implemented in the NEXRAD[1].

[1] To illustrate the issue, some work has been sponsored by the OSF to improve data quality (e.g., automated recognition of ground clutter versus weather) within the ORPG, but the resulting base data after editing has not been provided to the full automation users of base data to determine how effective the data removal is in automated product generation applications. Also, there has not been testing at a variety of beta test locations as suggested in the NRC report

Providing these base data streams to developers of automated algorithms that use NEXRAD data will be greatly facilitated by the use of the LDM data compression/Internet 2 data transmission approach.

By providing these data streams prior to formal NEXRAD deployment will enable the users of the base data to understand the capability provided by the proposed enhancement and allow them to provide feedback to the data quality algorithm developers of issues that need to be addressed.

2. Use of data from other sensors in an integrated observation system to identify data quality problems with a NEXRAD. In some cases, it is difficult to assess the quality of NEXRAD data (e.g., one has suspicious reflectivity data with no corresponding velocity or spectrum width data) from an individual NEXRAD alone. Comparison of the data with data from other sensors (e.g., other NEXRADs and/or FAA radars) can help identify problems with a NEXRAD.

An integrated observation system and boundary layer wind sensing

In addition to base data quality improvements discussed above I suggest that there be research on ways of improving boundary layer wind sensing. This is very important for forecasting the full life history of convective storms and may be very important for the detection / prediction of small tornados that are not associated with mesocyclones.

Even if one uses TDWR in conjunction with NEXRAD (see fig. 1), there are many regions where there is not adequate boundary layer wind coverage. However, there are technical concerns with the small gap filler radars proposed in the NRC report because they are at X-band, which scatters less from refractive index perturbations than lower frequencies such as S-band or L-band. Also, there may be difficulties with range/velocity folding when one seeks to sense clear air returns at X band.

It is likely that there will be upgrades to the existing FAA ATC en route and terminal primary radars as a result of Sept. 11th. Hence, the NEXRAD program should closely monitor what is being done to these radars to see if there is an opportunity to utilize those radars for boundary layer wind sensing.

Response from Forsyth

WEATHER RADAR 2007-2020

By 2007, Dual-Polarization should have been implemented on the WSR-88D. Not only will dual polarization improve precipitation estimates from radars, but it will also enhance our ability to discriminate hail from rain and gauge the hail size, identify precipitation type in winter storms, identify electrical active storms, identify aircraft icing conditions, and identify anomalous propagation and other scatters (i.e. birds, bugs, and chaff). This will again be a great advancement in the use of weather radars for the improvement of weather forecasts, warnings, and flight safety.

Advances in the use of dual-polarization, along with new schemes to reduce the range-velocity ambiguities, will improve the use and effectiveness of C-and X-band radar systems. These could prove to be important in gap filling for the larger S-band network and providing better low-level coverage through out the nation for the detection of severe weather.

Additional technology beyond 2007 includes the phased array antenna. The testing of Phased Array radar systems for observation of weather has already begun. This is reminiscent of the developments of Doppler weather radars in the late sixties and early seventies using military technology to improve the state-of-the-science in meteorology. The capabilities of phased array systems will allow us to optimize our scan strategies and identify pre-cursors of dangerous phenomena quicker. It will provide the meteorologist with volumetric views of the atmosphere five to six times faster then possible on the WSR-88D. Areas of potential severe weather will be investigated with finer time and space resolution. These systems will have to be dual polarized to take full advantage of these capabilities. I envision a capability for triple use of the radar for tracking of weather and aircraft simultaneously and providing wind profiles. Improved detection of severe weather and better conceptual models of the atmosphere will result from the use of phased array weather radars. Advanced display technology will allow for 3- and 4-Dimensional visualization of weather radar products in real-time.

In addition, with the improvements in communication bandwidths, I see combining of various radars (i.e. WSR-88Ds, TDWR, ARSR-4, TV radar systems, phased array systems, mobile systems, etc.) into a real-time radar database that is then used to provide the best radar information for any given location. This database will then initialize storm scale models that will be run every several minutes to produce a new 30 min to 2 hr forecast. I also see combining of multiple data sources (i.e., radars, satellites, profilers, mesonets, etc.) to provide an improved atmospheric picture to the meteorologist.

For example, the radar is an imperfect sampler of the atmosphere. The farther from the radar, the greater the resolution volume, and therefore more space averaging occurs. Our conceptual models will improve to the point that we can use multiple sources of meteorological information to find the correct template that matches the atmospheric phenomena of interest. Thus, an improved ability to interpret correctly what is really happening at the ground at ranges from the radar where the earth curvature and beam averaging become a problem.

The system must remain flexible and open to new ideas. For example, as we learn more about how tornadoes form, we may find pre-cursors to these events that may require new technology to observe. We need to continue to support the basic research that will allow for these new technologies to development and be tested in order to improve our abilities to provide the best hazardous weather warnings and forecasts possible.

Response from Keeler

The WSR-88D is destined for a long and fruitful life. If history provides any guidance, the 88D will be around for another 3 decades or more. Much can be done with the existing system to enhance its utility to society. I group my bulleted list of WSR-88D and future system upgrades into 1) present trends that are already underway, 2) short term upgrades for a maturing 88D that seem entirely reasonable to pursue with the existing 88D RDA, and 3) long-term upgrades (actually developments) that require a new radar system, specifically a new RDA system. Many of these are discussed in detail in the NRC report, "Weather Radar Technology beyond NEXRAD", for which I was a contributing author. Therefore, my present views are highly influenced by that report.

Present trends of WSR-88D (2002-07)

- Open RPG
  - Algorithms easily added, deleted, revised (e.g., Refractivity/water vapor)
  - Data distribution and archiving via CRAFT techniques

- Open RDA
  - Data quality upgrades -- RV Mitigation, enhanced AP Mitigation
  - Spectrum processing and other advanced processing techniques

- Polarimetric data
  - Better precip estimation (?), especially near ground level
  - Hydrometeor particle identification
  - Improved data quality (separating precip from other scattering)

- ROC implementation process is typically quite long – attempting to reduce it.

Short Term: Mature WSR-88D upgrades (2005-2025)

- Advanced processing techniques
  - Adaptive waveform selection and processing
  - Multi-thread processing (sensitivity and spatial resolution, data quality, pulse compression, AR spectrum analysis, ...)

- Radar data will be primary data source for multiple, complementary sources for integrated observing systems

- Data assimilation for site specific products
  - Enhanced AWIPS capabilities
  - Accurate observational error statistics

- Exceptional data quality as spectral processing techniques evolve (a la Profiler techniques used with much lower data acquisition rates)

- Site dependent processing
    - VCPs and product suites
    - National network products

- Mobile NEXRAD for temporary (emergency) deployments

- Integration of non-government radar data sources (Quality controlled data)

- Increased dependence on commercial upgrades (e.g., ORDA/RVP8 if it goes well)

- Communications and computing power to burn (optical and nano-technologies)

- Increased pressure for spectrum allocation at S-Band from wireless industry

- Advanced 3D interactive display technologies for forecasters

Long term: Next generation Weather Radar (2020-30) -- See NRC report

- Phased array, agile beam, short dwell time (fast VCPs)
    - Improved data quality by terrain following to reduce clutter
    - Faster VCPs and data update rates for faster warnings

- Networks of supplementary short range radars
    - PBL coverage in selected areas (/cities/airports)
    - High resolution measurements in PBL
    - Reduced bright band problem

Response from Preston

Some radar thoughts and additions for the book.

Page 12 - Consider adding the Army Corp of Engineers (COE) and US Bureau of Reclamation (USBR) to the list of federal agencies that use WSR-88D data especially in the operation of dams and the hydrologic flow models.

The TAC may want to consider how the WSR-88D will be integrated with the NWS and other agency forecast changes into a digital format. In short term forecasting the WSR-88D will continue to be of great assistance and being able to incorporate data directly into girded display forecasts for Internet and other user venues is a must.

Having worked operationally with the 88D in Kansas, Oklahoma and now Idaho as well as teaching at the ROC, there continues to be a high variability of what the radar is used for. Since my last 4 years have been at WFO Pocatello and previous 4 years as NWS Western Region NEXRAD Program Manager, let me pass along a few items that continue to plaque us in the west.

1. The VCP time sequences. I know that new builds will introduce a couple of new VCPs, we'll have to wait and see how these react to our pulse thunderstorms. Allowing the user to have VCPs with rapid update times for mid-level detection of cores that are dropping are essential to increasing our warning lead time. I realize other users need a larger suite of derived products, but these could be produced once every 15 minutes, while quick VCP updates of 1-4 minutes with certain selected levels would provide the best mechanism in seeing micro/macroburst situations.

2. Beam blockage and Lack of Coverage. I believe the TAC should continue to review coverage patterns in the West. There are growing recreation and home areas, which have no coverage today (Central Oregon, Yellowstone Park, 4 Corners Area). If we are to provide the best product available, having radar data available in these and other areas is essential. Beam Blockage also is notable in several of the West's radar locations. Combining FAA radar data at certain airports is a plus, but we may need to consider more sites in the future.

Certain radars in the west are located on mountain tops (Medford, Missoula, Cedar City) just to name a few. The TAC should consider changing the original charter for 0.5 degree as the lowest operational level for the 88D. In fact, at MSO and MFR the old WSR-57 system normally ran at -0.5 degrees.

In reviewing the pre-publication book, I believe the committee has some excellent goals and recommendations. Not too much more to add.

Response from Smith

1. Near-term developments
The flexibility provided by the open systems architecture will enhance the access to, and the utility of, the WSR-88D data. Digital receiver technology, which could be implemented in the near future, will also help to improve the overall data quality. Algorithms developed outside the formal configuration management process are likely to proliferate in the future. Data fusion – synthesis of radar with other types of weather data – and development of specific user-oriented decision aids are likely to accompany these developments. Requirements to assimilate the data (probably winds first, with other features coming later) into numerical models will be one driving factor. Visualization technology, developed largely by the entertainment and gaming industry, will offer improved ways to depict and analyze the radar data.

The near future is likely to see a polarimetric upgrade on the WSR-88D, although benefit/cost issues need to be resolved before its implementation. While much of the attention has focused on potential improvement in rainfall measurement, the polarimetric features may provide the greatest help in the area of improved data quality.

2. Far-term prospects
At some point perhaps 20 years hence the NEXRAD systems will be nearing the end of their useful life. It is not likely that its replacement will duplicate the current design; advanced capabilities already available and in the development process will permit various enhancements. Benefit/cost considerations will be needed to determine which of these capabilities should actually be implemented in the next generation system.

Among the likely candidates are:

Solid-state transmitters: If satisfactory levels of power output can be achieved, these will enhance the overall system reliability. That is especially the case if the design requires a capability for generating wideband waveforms.

Phased-array antennas: These offer the ability for rapid, and perhaps more importantly, adaptive scanning to focus more of the attention on the weather targets of primary interest. That can provide various combinations of better resolution in space, time, and the variables of interest. Phased-array antennas tend to be expensive, so cost issues will have to be addressed. The radars may be designed to serve multiple functions in an effort to spread the costs, but the history of multifunction radars has not been particularly encouraging. Also, it is not yet clear that such antennas can maintain the quality of their polarization characteristics at squint angles very far off the major axis. That may restrict the ability to transfer important polarimetric capabilities to the new systems.

Small "boundary layer" radars: As numerical weather prediction models improve and operate at ever-smaller scales, the requirements for input data on boundary layer winds and moisture distributions will increase. Large network radars like the WSR-88D provide boundary layer coverage only over less than 10% of their primary surveillance area. If smaller radars, probably operating at higher frequencies, can be made sufficiently cheap and reliable, they could be installed at much closer spacing to provide the requisite boundary layer coverage. That would permit determination of dual- or even multiple-Doppler winds, and the overlapping coverage could circumvent many of the attenuation problems. Refractivity measurements using ground targets could provide much of the needed water vapor data. These radars could also provide better coverage in mountainous regions than could the larger NEXRAD-type radars. For these radars to become feasible, issues of sitting and maintenance requirements would have to be satisfactorily resolved.

3. Frequency, bandwidth, and power constraints
Pulse radars use substantial blocks of increasingly valuable space in the electromagnetic spectrum. Competing interests may well drive available allocations for weather radar out of the currently favored S-band. At higher frequencies, concerns about attenuation by precipitation, and even by clear air, increase and the Doppler dilemma poses more difficult challenges. Moreover, constraints on power output or bandwidth may restrict the technological options that could be implemented. These things would tend to favor adoption of the small, low-power “boundary layer” radar approach if the cost and reliability concerns can be surmounted.

Response from Spaulding

Background: The Air Force Weather (AFW) community has no validated new requirements for the WSR-88D but several undefined requirements for things like base data ingest and faster updates. They would also like easier ways to get the latest radar products and the Army is interested in radar data to support Homeland Defense. Finally, the maintenance community is always looking for a system that is more reliable and easier to maintain. I will address these issues separately.
Operations.

Base Data Ingest. The Air Force Weather Agency (AFWA) Strategic Center has an unvalidated requirement to ingest radar data into their models. At this time there is no project to perform work needed to ingest this data into the models. When this was first discussed the dates mentioned were sometime in 2005-2007 timeframe. AFWA may be able to leverage off the NWS plan to centrally collect base data. They could get all the data from a single source rather then going out to the individual radars. This requires no new changes to the radar.

Faster updates. Both the AFW and flight operations communities occasionally raise the issue of “real-time” radar data. While there is work being done on new volume control patterns (VCP) including a “faster” update there are perceptions that since the data isn’t “real-time” it isn’t good enough for the customer. There appear to be two different requirements for faster updates.

The first requirement is the need to provide weather advisories when there is lightning (thunderstorms) within five nautical miles of a base or fort. This came out of several cases where military personnel were killed due to lightning strikes. And while the bases and forts have access to the national lightning network, management remembers when we issued advisories similar to this with the FPS-77 and FPQ-21 and feels we should get this information from the WSR-88D.

The other requirement that gets mentioned occasionally is location of thunderstorms for aircraft avoidance. While this requirement hasn’t been documented it has been mentioned several times.

While I believe both of these requirements are more of an education issue then a requirements issue, a phased array antenna could significantly speed up the VCPs. The data wouldn’t be “real-time” but it would be timelier. If we relied on faster VCPs with the existing antenna we increase the wear-and-tear on the antenna and these VCPs would take longer then VCPs done with a phased array antenna.

Updated communications. Currently to get timely data from a WSR-88D you need a dedicated circuit to the radar product generator (RPG). Connecting each radar to the Internet, specifically Internet II, would allow us to eliminate the point-to-point dedicated communications needed to acquire radar data. While there is radar data currently available over the Internet it is a sub-set of available products, you can’t make one-time requests, and is generally 15+ minutes old. This would require both hardware and software changes at the radar, software changes at the user end, changes to the communications, along with meeting security requirements that could be severe enough to never allow us access the radars in this manner. There is a current Configuration Change Request in the project pool to look at this requirement but no work scheduled. This solution would possibly meet communications requirements for users like Homeland Defense and others that only have a non-routine requirement to access the radar.

Homeland Defense. An initial test using the WSR-88D to detect simulated releases of agents was inconclusive although there are some people that feel there was some usable data from the returns. A new VCP was created for the test; it was 0.5^{o} elevation scans only. This VCP may have been optimal for biological or chemical release but it doesn't give adequate coverage for weather. To support Homeland Defense and the primary job of weather support would require the ability to perform VCPs very rapidly. This seems to imply it would require a multi-faceted and/or rotating phased array active antenna.

Maintenance.

There is a perception that the only things that get changed in the radar are those that "improve" operations, sometimes at the expense of maintainability. We have included words about reliability and maintainability in projects but reality is primary focus is improved operational capability and software maintainability.

There have been a few generally small projects to improve the reliability of the system. These have had varying levels of success.

We have had some significant improvements with the Static UPS TPMS, lightning bonding retrofit, improvements to the Back-swing Diode Stack, and the AC Ducting Modification.

But we also have made some serious missteps. Examples are the TPMS with the Roselle Motor Generator and the Specific Systems air conditioning units.

And then changes to the trigger amplifier have been both good and bad.

Looking at parts usage for the radar, there are three critical items that are replaced almost yearly at every radar site. One of those is in the receiver that will be replaced by Open RDA. The other two are transmitter parts. While the National Reconditioning Center (NRC) continually looks at improving reliability of individual parts in the transmitter and elsewhere, there isn't any project to find a transmitter that is more reliable then the current one.

The "Weather Radar Technology Beyond NEXRAD" report says solid-state transmitters lack the high peak power pulsing capability we currently have. There are members of the Air Force maintenance community that feel there are systems out there that can support the WSR-88D. These need to be investigated and if it requires modifying the scan strategy to go to pulse compression then that needs to be looked at also.

There are members of the maintenance/engineering community that believe there are conventional transmitters currently available with output power in the same range as the WSR-88D that are more reliable then the existing transmitter.
There needs to be an active project to investigate transmitter replacement. It needs to look at both solid state and conventional transmitters.

The on-going NRC tasks of improving reliability of existing parts must continue.

Summary: It looks like a phased array with active antenna would meet requirements for real-time updates, Homeland Defense, and replacement of the existing transmitter. Understanding there are a lot of technical issues that will need to be solved to make this happen I feel this would likely give us significantly improved capabilities. Not just for DoD but for all the agencies.

Response from Strawbridge

Our input will be from the point of view of the aviation user and will not generally address many of the concerns of the wider user community. This is a quite natural result of the familiarity we enjoy with the needs of aviation in general and the National Airspace System in particular, and our experience with the NEXRAD in that context. It also flows from our experience with the TDWR and the FAA's long-range en route radar.

For many years the NEXRAD community concentrated its efforts on improving the performance of the radar in areas other than those important to the aviation community. This is not an indictment of the motives of those involved in the effort but rather an admission that the aviation community in general and the FAA in particular were unaware, to a great degree, of the potentially great benefits to be derived from NEXRAD in terms of enhancements to both traffic management and safety. As the experience level of the FAA grew with the implementation of TDWR and ARSR-4 and as both ITWS and WARP were coming on line, the FAA became much more intimately involved in the process of NEXRAD enhancement. This involvement continues at an accelerating pace.

It is our belief that one of the most potentially fruitful areas for development is to continue the work begun by the FAA with the ITWS program. The integration of a multitude of weather sensors into a single coherent system with automated products such as very accurate two-hour forecasts for such things as storm motion and storm cell growth and decay has been accomplished in ITWS. It is our belief that this work should be extended to cover all heavily traveled air routes within the continental United States. As a matter of fact there is currently in place a proof of concept system, the Corridor Integrated Weather System (CIWS), which will, when completed, include data from NEXRADs, TDWRs, ASR-9s, and ARSR-4s. The architecture for this system is somewhat different from the architecture used by ITWS since the area covered by the system is so much greater than for any single ITWS.

The potential for traffic flow improvement for CIWS has only begun to be tapped. At this point only weather tools have been deployed on this system. If traffic flow tools can be successfully integrated into CIWS so that its potential can be maximized while at the same time minimizing workload for Traffic Flow Management personnel, the probable improvement in delay figures due to weather is enormous. The economic benefit to the airlines, and ultimately to the flying public would, likewise be large indeed. The job cannot truly begin however until the optimum integration of weather sensors and the development of better aviation oriented products is much further along than it is currently.

Thus far we have discussed only short-term weather prediction products. It is conceivable that such short-term technology could feed into and perhaps improve midterm predictive models. We feel that this is an area that needs to be explored. As these products are improved in both detail and quality, their use as predictive tools for aviation would be eagerly welcomed. So it appears that the work will need to be iterative in nature. That is the short term, nearcast type tools will have to be improved, then their output will have to be tested as input to mid-term products, and if useful then the mid-term products will have to be optimized taking into account the new inputs. At such time that these mid-term products prove viable, they could be integrated by the FAA with whatever TFM tools that might be appropriate to achieve even better results for the flying public.

The optimum system would be one that would take inputs from ALL available sensors nationwide, integrate these inputs, apply algorithms to produce automated products and then disseminate these products to all interested parties. More practically, inputs from the most capable sensors should be integrated, massaged through algorithms, and then products distributed to parties with vital interests in them.

In any case, we feel that the major mid-term effort should be in integrating existing sensor outputs with the output from the NEXRAD, and developing automated products that would be more useful to non-meteorologist end users. Every effort should be made to ensure that there is no duplication of work by the various government and non-government organizations involved in this effort. Perhaps the task of serving as a clearinghouse for developmental efforts could be given to the TAC.

Response from Walton

From an operational field perspective I see major advances in NEXRAD's integration into other emerging technologies. Merging radar with Geographical Information Systems (GIS) will yield huge strides in forecast services. In the area of hydrology, integrating the radar data with virtual reality technology in GIS with other data sets such as, geo-political, soils, topography, vegetation, and land use, will enable the forecaster to issue more timely and accurate products. In the area of meteorology, integrating the radar data with spotter and emergency services databases so that the forecaster can look at the emerging weather and just point and click to communicate with spotters and emergency services would be very beneficial.

Development of graphical 3-D products and enhanced display capabilities will aid in the forecast decision process. Future radar graphics must incorporate virtual reality technology in GIS-based hydrologic and meteorological modeling. This will allow the forecast to look at the weather from any angle they choose and to "fly through" the storm system.

Future radar systems must have the capability to ingest more real time hydrometeorological data to aid in the creation of products. Atmospheric profiles from model soundings such as the Rapid Update Cycle (RUC) and Local Analysis and Prediction System (LAPS) need to be incorporated into the next generation of product generation by the radar. The model data could be used by the radar algorithms to better deal with freezing levels/bright band as well as to enhance the TDA and Meso algorithms. Precipitation estimates by the radar could be greatly enhanced by incorporating rain gage data in near real time, however, the majority of NEXRAD sites do not have sufficient real time rain gage data underneath the Radar umbrella to pull this off. Satellite data could be utilized by the radar to detect AP in clear air. Radar should use ASOS, Vertical Wind Profiles, and future automated COOP data to help determine precipitation type and rainfall rates. We need a more synergistic approach to fine tuning the radar algorithms and this all can be accomplished by incorporating additional model and observational data sets in real time into the NEXRAD data stream. A good example would be to incorporate model data in an underlying GIS so that NEXRAD algorithms could utilize this data to generate output based on varying meteorological conditions over the scope of the radar, such as freezing levels or wind shear.

Future radar systems must not be restricted with respect to detection of hydrometeorological targets below a half of a degree.

Our technicians would appreciate it if our future radars where able to obtain data from the Naval Observatory in real time and conduct automated sun checks (sun checks are manually done each month now).

Response from Whiton

As suggested by your letter, these inputs to the strategic planning process should be focused on the time from 2007-2020 rather than on the weather radar technology beyond NEXRAD dealt with in the National Research Council (NRC) report. The one exception to your suggestion is the item directly below:

WSR-88D Replacement System (2020-2025 Time Frame)

Cost and frequency allocation considerations should not be allowed to drive the WSR-88D replacement system toward a less capable design that does not fully meet the historically agreed upon objectives of the nation's weather radar network. Long-range detection of precipitation and severe convective storms, without the effects of attenuation, drove the network design in the 1950s. Except perhaps for the emphasis on hurricane detection by radar, the same objectives would pertain today. The NRC report mentions multiple-Doppler technology only in the context of auxiliary, short-range radars. Multiple-Doppler technology would definitely be useful in that context, but the trust of the section of the report seems directed at gap-filler radars operating at wavelengths shorter than the S-band. The NRC report mentions that polarimetric techniques may operate more effectively in the X-band than at the S-band, and the frequency allocation problems may be easier to solve. Other performance aspects of supplementing the weather observing system with other radars, such as gap filling and severe-storm identification, would be just as effective, if not more so, if all the radars operated at the S-band. One of the Joint Doppler Operational Project findings (Allen et al. 1981) was that even a C-band radar can be too severely attenuated by intervening precipitation to be effective in severe-storm identification. Admittedly, shorter-wavelength radar components cost less than comparable S-band equipment. Cost should not be a driving concern if acquisition of the supplemental radars is budgeted far enough in advance and there is a consensus among the participating agencies.

2007-2020 Time Frame

Introduction of a polarization diversity capability to the WSR-88D system is very important, particularly from the point of view of improving precipitation processing. It is probably the single most important thing we can do now to improve the WSR-88D and prepare for the replacement system.

Some of the advanced radar technologies being considered for the replacement radar system, such as rotating phased-array antennas, agile beam technologies, and advanced signal processing, should be investigated for potential use in the current system in order to reduce the time required for the volume scan, or volume coverage pattern, updates without adversely impacting data quality. If these and other techniques showed enough benefit for early implementation, the cost of the replacement system could be reduced correspondingly. Agency and Congressional fiscal scrutiny seems to intensify in relation to the total acquisition cost of replacement systems, whereas modifications are considered normal and prudent to extend the life and effectiveness of the system.

Federal Meteorological Handbook No. 11 (FMH-11), Doppler Radar Meteorological Observations, should be updated more often that it is. Whenever the theory and basic capabilities that lie behind the system change, or changes occur in processing, products, or operations, FMH-11 should be updated. For example, it is likely that polarization diversity will be added; in that case, corresponding changes should be make to the parts of FMH-11. Putting a version online should be the procedure to follow with FMH-11, as a printed edition can be produced from the softcopy. The online version should be produced in such a fashion that it has all the content of the printed version and is capable of being searched and copied.

Base data from the Open Radar Data Acquisition (ORDA) unit and the Open Radar Product Generator should be made available without restriction to Government agencies, companies, and the public in as close to real time as possible on the Internet II, now I design and prototype testing. This might reduce, if not eliminate, the need for some dedicated circuits now in use.

Calibration issues never seem to go away completely, despite introduction of advanced radar technology designed to make calibration easier or automatic. Now, the ORDA is expected to introduce a digital receiver with automatic calibration capabilities. Whether these capabilities will actually fix any potential calibration problems is uncertain. Some remaining unmeasured sources of error, such as the effective antenna system gain, or unexpected changes in the system, such s feed horn alignment, may be responsible for the difference between radars and other performance problems noted. An effort should be made, throughout the WSR-88D network, to measure anything significant to calibration that has not yet been measured and check anything that may inadvertently have changed. Perhaps, where radar coverage overlaps, automatic comparisons should be made between the equivalent radar reflectivity factor of a given target as viewed by each radar. Of course, these targets would have to be viewed using the same sampling volume within the precipitation system, and cases where beam filling is not comparable between storms would have to be removed. Any significant differences revealed by these comparisons should trigger recalibrations, as necessary, until the difference is explained. The benefits of calibration may justify the allocation of engineers ad technicians.

Research should be conducted to enable today's storm-series algorithms, which are based on centroid tracking and forecasting, to evolve to the use of storm-scale numerical weather prediction models.

A polarization diversity capability and oversampling/whitening (0.5-degree/0.25-km resolution radar data) are likely to be added to the WSR-88D in the next several years. Research should be conducted to determine the extent and impact of any incompatibility between polarization diversity and oversampling/whitening.

The WSR-88D data should be archived in popular geographical information systems format, especially ESRI ArcGiS formats, so users of these systems can ingest the radar data, apply overlay maps, display the composite, and perform other useful functions.

References

Allen, R.H., D.W. Burgess, and R.J. Donaldson Jr., 1981: Attenuation problems associated with a 5-cm radar. Bull. Amer. Meteor. Soc., 62, 807-810

Response from Wilson

It is assumed that by 2007 that:

1. *Dual polarization and signal processor*- The NEXRAD will have dual polarization capabilities and a new signal processor.

2. *Expanded network* - The primary limitation of the present NEXRAD network is the lack of coverage at low levels. This heavily impacts useful ranges for rainfall estimation, severe storm detection, convergence line detection, snowfall detection and precipitation estimation, boundary layer wind estimation and precipitation nowcasting. The only way to remedy this problem is with more radars closer together. Thus a high priority is to include all suitable radars into a national network. It is assumed the network would include the TDWR's by 2007. This should be expanded to include select FAA/ASR's, commercial and research radars.

   Every effort should be made to incorporate scanning angles below 0.5 deg. Experience with research radars has shown that scanning at an elevation angle of 0.0 deg instead of 0.5 deg can extend for 10's of kilometers the low-level clear-air return and detection of convergence lines. Also the lower angle can extend the range of observing very low-level features like microbursts. In addition the desirability of using negative scanning angles at elevated sites has often been proposed.

3. *Low-level mosaic* - As a minimum the data from this expanded network should provide a mosaic of the lowest available height. This was done for IHOP and was particularly useful for convergence line identification and was a favorite of forecasters.

<u>Possible by 2007 but overlooked</u>

The following would be possible by 2007 or shortly there after but I am not aware they are being considered. Because of the great impact they can have on furthering warnings and nowcasts they are listed here.

1. *Wind retrieval* - Implement single Doppler boundary layer wind retrieval techniques on the network radars. This has already been accomplished for several experimental operational programs (SCAN and RCWF) on NEXRAD's and a TDWR. In addition to the obvious applications for storm nowcasting and assimilation by models these winds can be very useful for homeland security associated with chemical releases.
2. *Radar refractivity* - Implement radar refractivity retrievals on network radars. This provides the ability to retrieve the near surface water vapor field around each radar. This is a particularly new and exciting development that has major implications for improving convective storm nowcasting. This was implemented on S-pol for IHOP and produced much interest among scientists and forecasters. The need for detailed mapping of water vapor has been stated by a variety of national scientific committees as a primary factor limiting the prediction of convective storms and quantitative precipitation.

3. *Boundary map* - Prepare a national map of boundary layer convergence lines. While this would make use of automated boundary detection algorithms like MIGFA it would utilize surface stations, satellite and numerical model diagnostics, as well as input from forecasters. Such an effort was planned for the NWS THOR program for this year but the program was postponed. This boundary analysis would cover scales from synoptic fronts to gust fronts to small lake breezes. It is felt by many forecasters that such an analysis would be very helpful for convective storm and severe storm nowcasting.
4. *Data quality* - The incorporation of dual-polarization on NEXRAD and a new processor just prior to 2007 will provide the opportunity to greatly enhance data quality. It is likely that data quality improvements will extend beyond 2007. Fuzzy logic algorithms will utilize polarimetric data to identify the various precipitation and non-precipitation targets. Non-precipitation targets such as fixed and anomalous ground clutter, sea clutter, planes, and birds could be detected and removed. Insects should be identified but NOT removed. Since particle-typing algorithms already exist and presently being enhanced it should not require significant new efforts beyond 2007.
5. *Severe storm warnings and nowcasting* – Further improvements to increase lead times for tornado and severe storm warnings are reaching a plateau and are primarily tied to more rapid radar data updates, azimuth over sampling to increase resolution and addition of FAA radars to increase resolution and decrease overshooting. More significant improvements will require the inclusion of forecast variables based on better understanding of tornado and severe storm formation. This will require an expert system approach. In fact some recent promising experiments where conducted where severe storm detection criteria from NSSL's WDSS were combined with convective storm nowcasting parameters from NCAR's Auto-nowcaster.

2007-2020

Dual-wavelength – It is unknown at this time whether it would be cost effect to add a second wavelength to NEXRAD. A second wavelength will be added to S-pol during the next 12 months. Findings from research activities with S-pol should be watched for applicability to operations.

Bistatic receivers - The use of bistatic receivers to obtain three dimensional wind fields in the vicinity of a NEXRAD have been considered but extensive tests have yet to be performed. S-pol and the McGill radar do have bistatic receivers. Results from experiments with these radars also need to be monitored for applicability to operations.

Data assimilation and data quality – Assimilation of radar data within numerical models is slowly gaining momentum and will continue to increase for some time. It is very important that radar data be of highest quality for this activity to proceed smoothly. The radar community has a responsibility to make certain that every effort is made to provide a clean data set. Data quality has always been the highest priority on the TAC Technical Needs List. It should continue to remain that way for this reason.

New paradigm – I recommend the TAC and NEXRAD program broaden its view beyond NEXRAD and take a more active role in the integration of radar with other sensors into a complete nowcasting system. The use of radar has matured to a point where it is no longer a stand-alone instrument, thus it should be considered as a piece of a total nowcasting system. Recently a USWRP workshop made recommendations concerning a national effort to establish test beds that would involve multiple agencies to fully exploit observational systems for the purpose of nowcasting. The test beds would be a place where new science and technology are infused into operations. They would incorporate established and new end users in their activities, and would serve as training conduits for both forecasters and users. While the emphasis in the USWRP workshop was on quantitative precipitation nowcasting it was fully realized it should include severe storm warnings. I propose that the TAC take an active role in nurturing the development of such test beds. The following is an excerpt from the USWRP workshop that is recommending the establishment of regional nowcasting test beds. Note that the NWS, FAA and NASA are proposed partners. It would make sense to also include the Air Force.

It is recommended that regional test beds be developed with access to unique research and observational data, archived data, and with users as partners are integral parts of the QPN activity. The test beds will serve as vehicles to accelerate science & technology infusion, to evaluate new techniques and products of benefit to end users, for training of forecasters with forecasters as partners, and to serve as a pathway to operations. The test beds will be regional in nature, and are expected to remain in place for several years at each location. Activity within each test bed may differ, but they will all build on past experiences such as Atlanta 1996 and Sydney 2000. They will utilize and expand on existing technologies such as SCAN, and will investigate optimum methods for combining expert and NWP techniques. The test beds will be a place where new science and technology are infused into operations. They will incorporate established and new end users in their activities, and will serve as training conduits for both forecasters and users. Among those expected to play strong roles within the test beds are university partners, government entities, and the private sector; it is expected that both undergraduate and graduate students will receive support as part of this activity. Within the test bed, a rich nowcast database will be developed that will support a variety of activities that range from fundamental convective scale research to verification and user needs assessment

Among the regional nowcast guidance products to be developed are ones that focus on: convergence lines, stability (water vapor), probability of convection (0-6 hr), multi-sensor products that are both probabilistic and deterministic for QPE and QPF, intensity of precipitation and categorical rainfall. End user products will be developed that address communication media and needs, such as verbal, graphical or pictorial nowcasts, and that allow for frequent updates, links to regional test beds, and verification.

A particular important data set will be a national convergence line product that contains convergence lines on multiple scales. This data set will initially be a mix of automated and human detections.

The cost of such test beds is high and can only be achieved by combining activities***. It is recommended that these test beds be joint with the planned FAA RCWF project, NWS THOR project and NASA Short-term Prediction Research and Transition Center (SPORT) program.*** Theses are all convective storm nowcasting activities. RCWF is planned to start this summer in the Northeast US from Chicago to New York. THOR activities are more uncertain but they would likely occur in the Huntsville AL area and Illinois/Indiana area. THOR is targeted for NWS Forecast Offices and RCWF for FAA aviation enroute and terminal operations.

Response from Zrnic

John there are two parallel evolutionary paths that the WSR-88D will take. These are 1) algorithm development and 2) radar development. Some of the algorithm developments (e.g., mesocyclone detection, initiation of storms, severe winds - note these last two I made up) are independent of the radar evolution and are routed in understanding of the phenomena. Other algorithms (e.g., those that use polarimetric data, spectral processing) require profound changes in the hardware and/or processing of radar signals.

NSSL is the designated (and likely the principal) NOAA R@D organization that looks into the future of the radar system evolution. Further NSSL is deeply engaged in researching hazardous weather phenomena and transferring its knowledge to NWS including algorithm development; Other NOAA organizations like FSL, Hurricane Lab, ETL are also involved in weather research. Further the NWS has priorities and cost beneficial improvements that I am not considering in this text. These organizations can give you complementary information especially about the development of algorithms.

Included here is a list of radar upgrades that I plan for the Norman radar. I give you two sets of dates: one for the Norman radar and the other for the network. Reasons for the upgrades are briefly explained. I start with algorithms and list only four that I think would be extremely useful. These and technological feasibility motivate the radar upgrades. You should contact others at NSSL, NWS, etc. for further information.

1. Algorithms

1.1 Tornado detection

Observations of Doppler spectra of tornadoes date to the early seventies. My initiation into radar meteorology was through studies of such spectra (recall the talk I gave at Purdue). Model simulations agree with observations, yet there has been no attempt to automatically identify the TSS for two reasons. One, spectral processing is not available on the network hence the efforts were, and still are, devoted to recognition of spatial distribution of mean velocities (Tornado Vortex Signatures). Two, scientists are more interested in understanding tornadoes, including measurements of maximum winds, than in developing artificial means to recognize the signatures. Automatic detection of vortices in the Doppler spectra is a difficult (plagues by velocity aliasing, artifacts) but doable (!) pattern recognition problem.

Thus I submit that advanced methods of tornado detection require spectral processing and analysis of data. Further improvement could be made if the spectra are obtained at increments smaller than the radar pulse depth. So I envision at least 5000 spectra per radial (5 over a resolution volume and 1000 range gates or one every 50 m). This can and will be done on the NOAA's Norman radar (KOUN1).

After the spectra are obtained, pattern recognition to identify a circulation within few contiguous (overlapping) range locations should be made. This is a job for the signal processor and although it has never been done we have some ideas of how to do it. The above requires spectral processing that should be on the Network in 2006.

1.2 Removal of artifacts and improvement in Signal to Noise Ratio (SNR)

Again spectral processing is well suited for adaptive removal of artifacts such as contamination by point scatterers (moving of fixed) and interference from radiation sources. Further a gain of about 10 dB in effective SNR can be achieved. This would extend coverage in clear air and unable better cloud (non precipitation) detection. Note that icing conditions and ceiling height are important for aviation.

To adaptively remove some of the artifacts (such as ground clutter) is easy (we know where to look for it); other detrimental receptions are more difficult to recognize. Worthy to explore are spatial continuity of spectra, use of "fuzzy logic" principles and physical relations between cause (artifact) and its spectral signature. The forthcoming new generation of scientists will explore without a doubt explore other avenues.

1.3 Classification of hydrometeors using polarimetric radar data

The basic algorithm has been developed at NSSL and OU. Much work remains to evolve it into a useful operational tool. That is to reduce probability of false classifications and increase probability of correct identification. The main obstacle, though, is verification.

Requires dual polarization that might be on the network after 2008.

1.4 Quantitative precipitation estimation

Estimation of rainfall using polarimetric data is quite mature. Improvements are ongoing. This is not so with snowfall for which we have not determined a method. Both require polarization.

2. Radar Development

Herein I list the technical changes planed for the KOUN1, brief reasons, and propose a timetable for both KOUN1 and the network.

2.1 Spectral Processing

Spectral processing is a prerequisite for most of subsequent signal manipulations. Hence it is a prerequisite (see following sections for the wheres, and whys).

Time table: KOUN1 – 2002 NETWORK - 2006

2.2 Range/velocity ambiguities

Phase coding (for low elevations) and staggered PRT (at higher than 3 deg in elevation) have been recommended but not tested.

Spectral processing of either waveform at about range 1000 locations is called for by both algorithms. This will be followed by verification and evaluation of the proposed algorithms (i.e., phase coding and staggered PRT).

<u>Expected outcome:</u> Decrease in censored areas (pink haze, effective increase in unambiguous range), increase in unambiguous velocity.

Time table: KOUN1 - 2002 to 2004 NETWORK – 3rd build 2007

2.3. Oversampling to increase rotation rate and/or reduce errors of estimates
Oversampling in range by a factor between 5 and 10 (this range is practically feasible) provides significant benefits. All the variables would have errors about $\sqrt{5}$ to $\sqrt{10}$ time smaller than in the current system (in regions of strong SNR). Therefore the errors would be the same if the antenna rotates at the current rates and ***samples at 0.5 deg in azimuth*** (that is the dwell time and number of pulsed is one half of what it is today). This has never been demonstrated, except with a stationary antenna and on about 100 range locations. The technique will require an increase in computation power and throughput by an order of magnitude over conventional techniques.
<u>Expected outcome</u>: Extended range of vortex detection, faster scan rates, smaller errors of all polarimetric variables, smaller errors in precipitation measurements.

Time table:

KOUN1	NETWORK
2003 (without spectral processing)	2008
2003 to 2004 (with spectral processing)	2010

2.4 Dual Polarization

This is a major upgrade on the network in hardware and processing power. Note that the three items 2.1 to 2.3 should be incorporated into the processing of dual polarization data. That is, spectral processing to obtain the variable should be made, in addition range and velocity ambiguities should be mitigated, artifacts removed, and all that on over sampled data in range! There should be no compromise in the computations 2.1 to 2.3, only now there are two channels and therefore twice as many range locations must be processes. Spectral processing of polarimetric data has not been done routinely but NSSL has made some tests on time series data.

<u>Expected outcome</u>: Superb classification of precipitation type and estimation of amounts will be possible. Separation of artifacts from signal. Superior performance in regions of anomalous propagation. Sub clutter visibility (measurement of rain in some regions where there is strong ground clutter, ditto for detection of tornadoes).

Time table:

KOUN1	NETWORK
2002 (through Sigmet receiver)	
2003 (new processor, no spectral processing)	
2004 – 05 (combined with oversampling)	(2008)
2006 – 08 (spectral processing)	(2010)

<u>**ULTIMATE OUTCOME**</u> - after all the 2.1 to 2.4 items are included: Best ever polarimetric Doppler surveillance radar with a classical design, and standard antenna! That is, radar data as clean as possible (least artifacts), best range velocity mitigation scheme, best rainfall snow fall etc, measurement, smallest standard errors of estimates, fastest rotation rates (5 rpm), best vortex detection algorithm, and so on...Corollary, much

lower false alarm rates on all algorithms, better probability of detection by all algorithms, improved performance of all algorithms (extended range, less censored data).

3. Schedule

The time tables I gave have larger uncertainty for farther forecasts but no more than about 1 year in the KOUN1 case. Moreover, the processor on the KOUN1 today has the power to do all the computations needed (except automatic detection of tornado spectra). Processing speed and throughput increase with time and NSSL will take advantage when needed. My projections for the NETWORK are educated guesses. Also I do not know the mechanism by which the technology described herein will be transferred. Even with a mechanism in place the question of how much to do at one time remains. I submit that the NETWORK need not go through all the incremental steps NSSL will take. For example polarimetric upgrade could include over-sampling and spectral processing in one shot, whereas at NSSL these are made by at least three different guns (Cimarron, then KOUN1 with Sigmet receiver, than KOUN1 with the new processor and digital receiver). After we firmly establish each step we can tell others how to make a leap.

My feeling is that it would be 2015 before all of the above is on the NETWORK. The principal reason is that this dwells into a supper high tech, hence manpower needs to be very highly qualified and that is expensive. Further NWS has moved away from large companies that maintain a steady pool of such people, or these companies realize that weather radar is a small business and therefore have abandoned it (Raytheon is out, Lockheed Martin got out but is considering coming back). Contrast this to the military radars where for work of similar difficulty the cost is at least an order of magnitude higher.